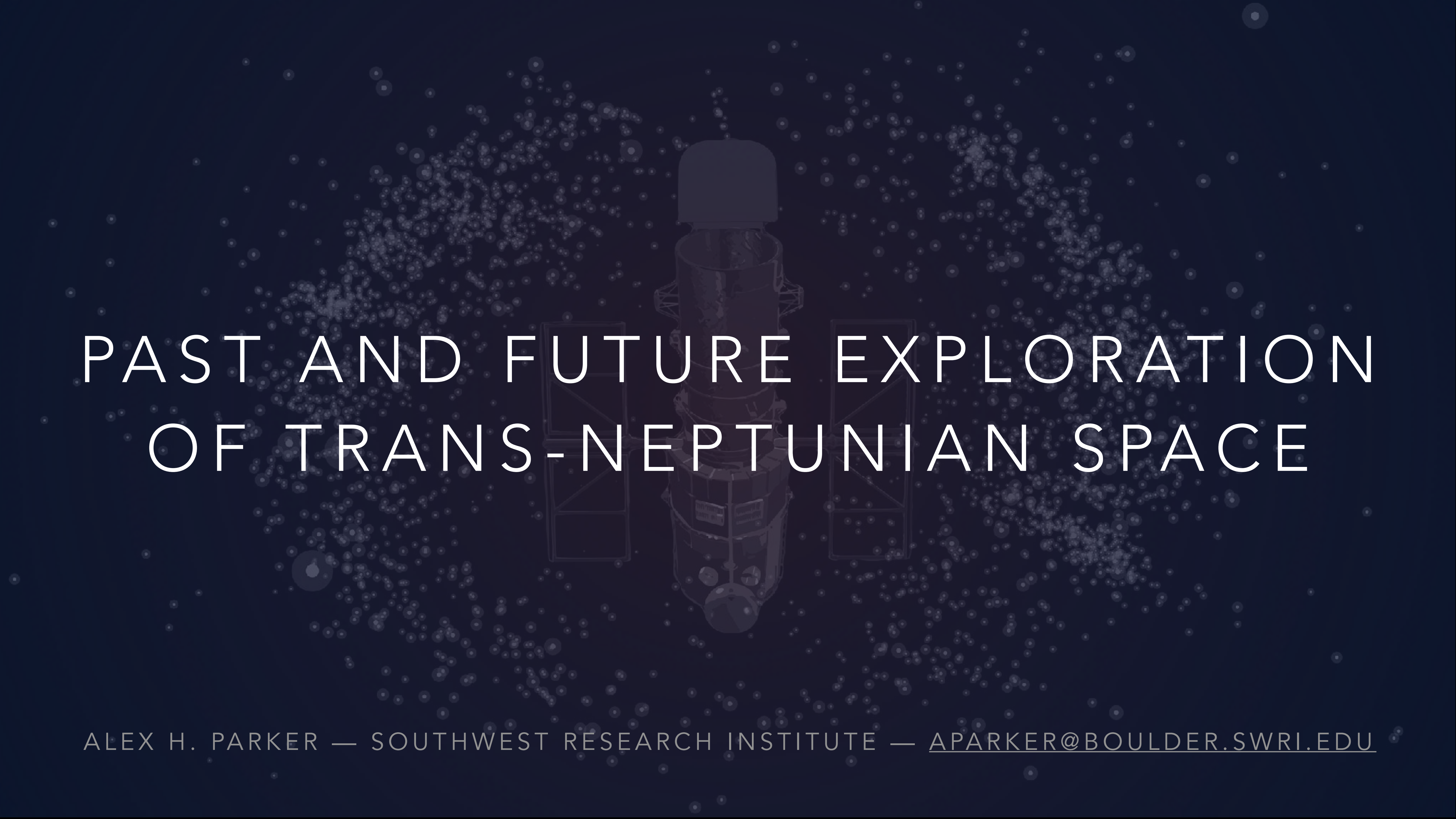




PAST AND FUTURE EXPLORATION OF TRANS-NEPTUNIAN SPACE

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STRUCTURE OF THE KUIPER BELT

- ▶ Resonant populations (e.g., Pluto in 3:2 mean-motion resonance with Neptune)
- ▶ “Classical” populations: isolated from Neptune’s direct influence and non-resonant.
 - ▶ Hot classicals are a dynamically excited sub-population
 - ▶ Cold classicals are a low-inclination, low-eccentricity sub-population
- ▶ Scattered disk: Non-resonant objects on Neptune-influenced orbits.
- ▶ Distant detached objects: excited objects on scattered-disk like orbits, but beyond the reach of Neptune.

Dynamical Property Distributions

- Direct detection with dedicated followup

Size-Frequency Distribution Analyses

- Direct detection
- Inference from crater records
- Serendipitous stellar occultations

Surface Composition

- UV-IR photometry
- UV-IR spectroscopy

Surface Temperatures

- IR-sub-mm photometry/spectroscopy

Bulk Densities

- Binary orbit + shape measurement

Rings Census

- Occultations
- In-situ observations

Binary/Satellite Census

- Direct detection
- Lightcurves
- Inference from crater records

Binary Mutual Orbit Distribution

- Direct detection with dedicated followup

Shape Distribution

- Lightcurves
- Multi-chord occultations
- In-situ observations

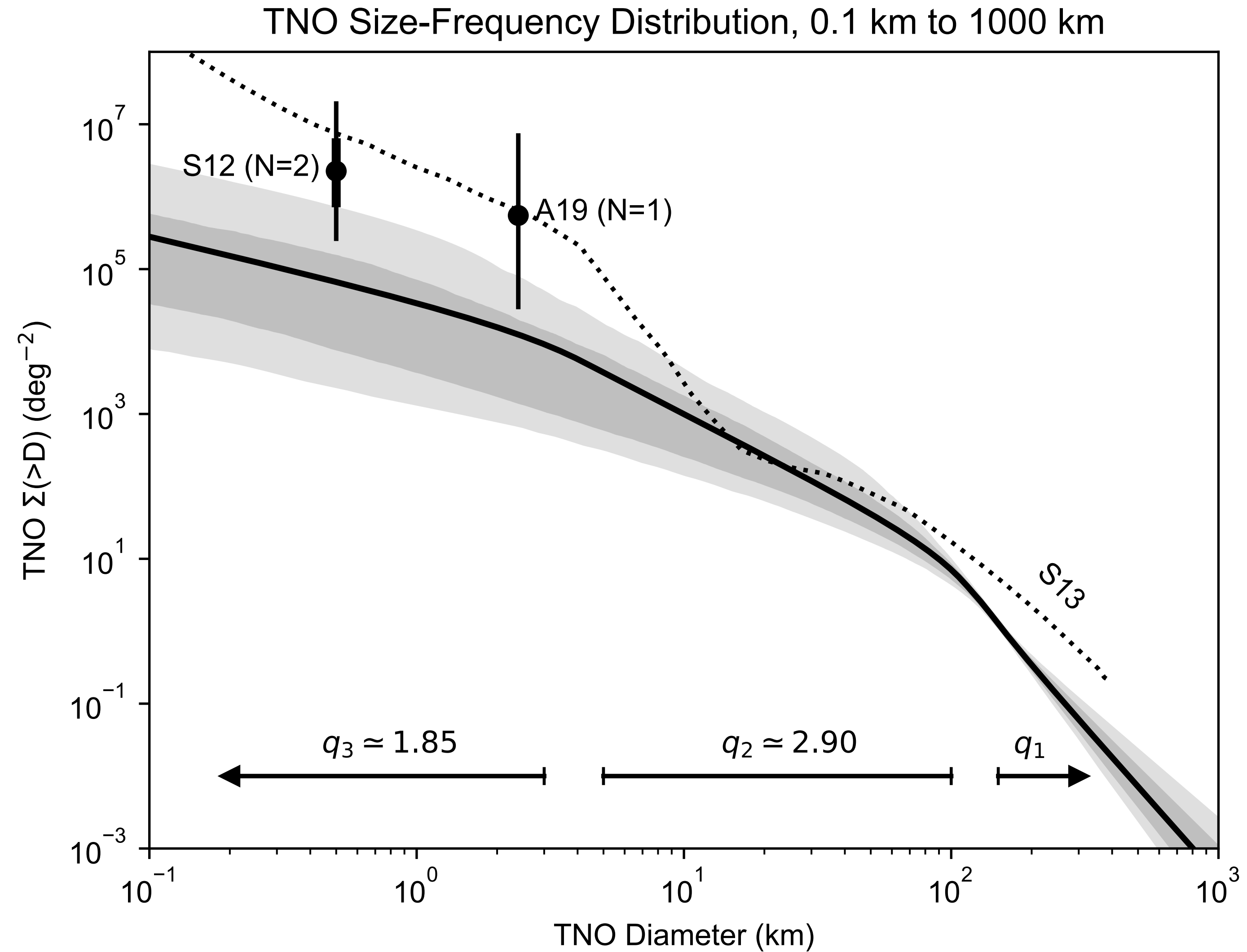
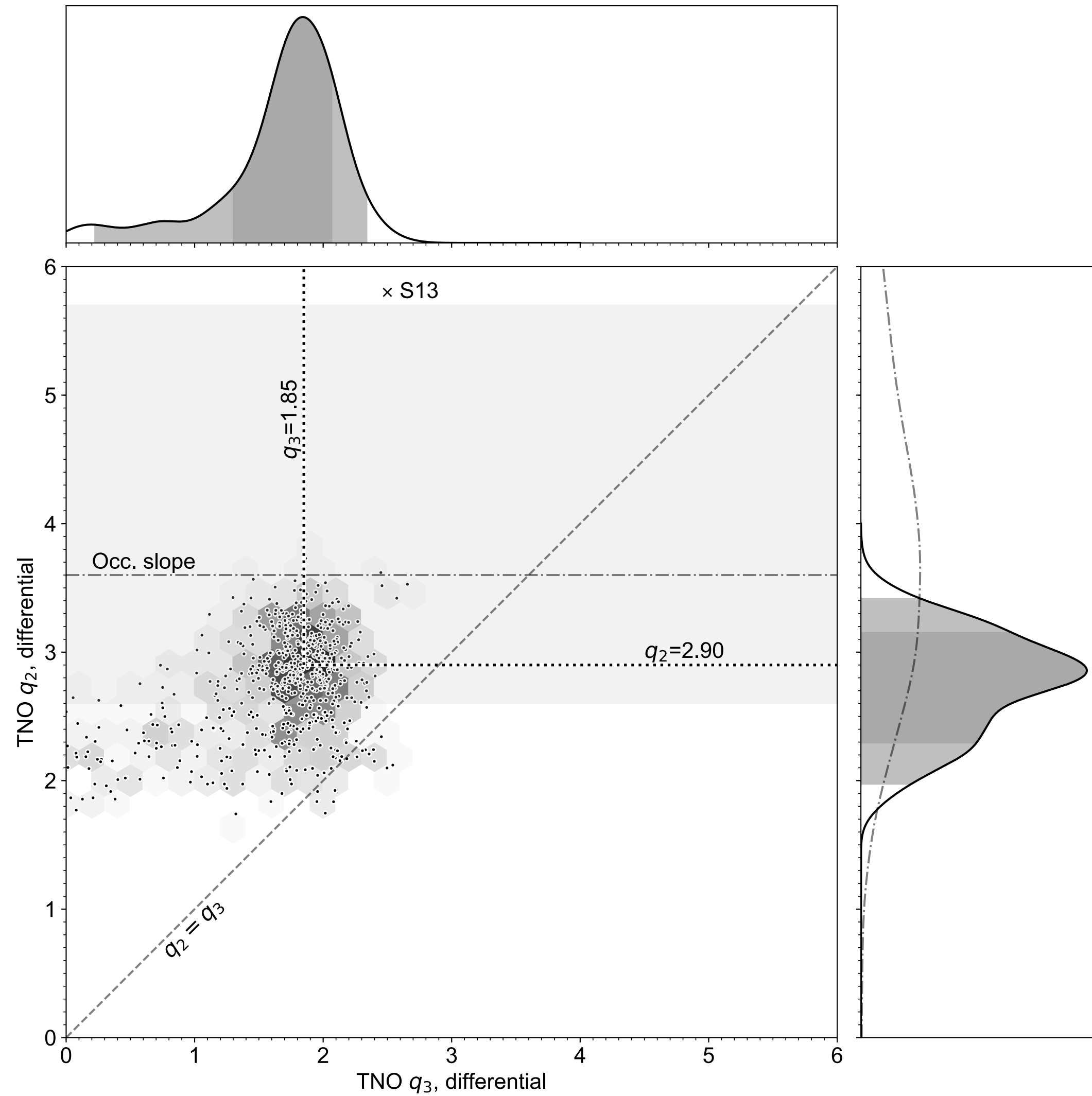
Atmosphere Properties

- Occultations
- In-situ observations
- IR-sub-mm spectroscopy

Geologic+Interior Properties

- Mutual events (surface features)
- High-resolution imagery (surface features)
- In-situ observations

Size-Frequency Distribution of TNOs from 0.1 to 1000 km

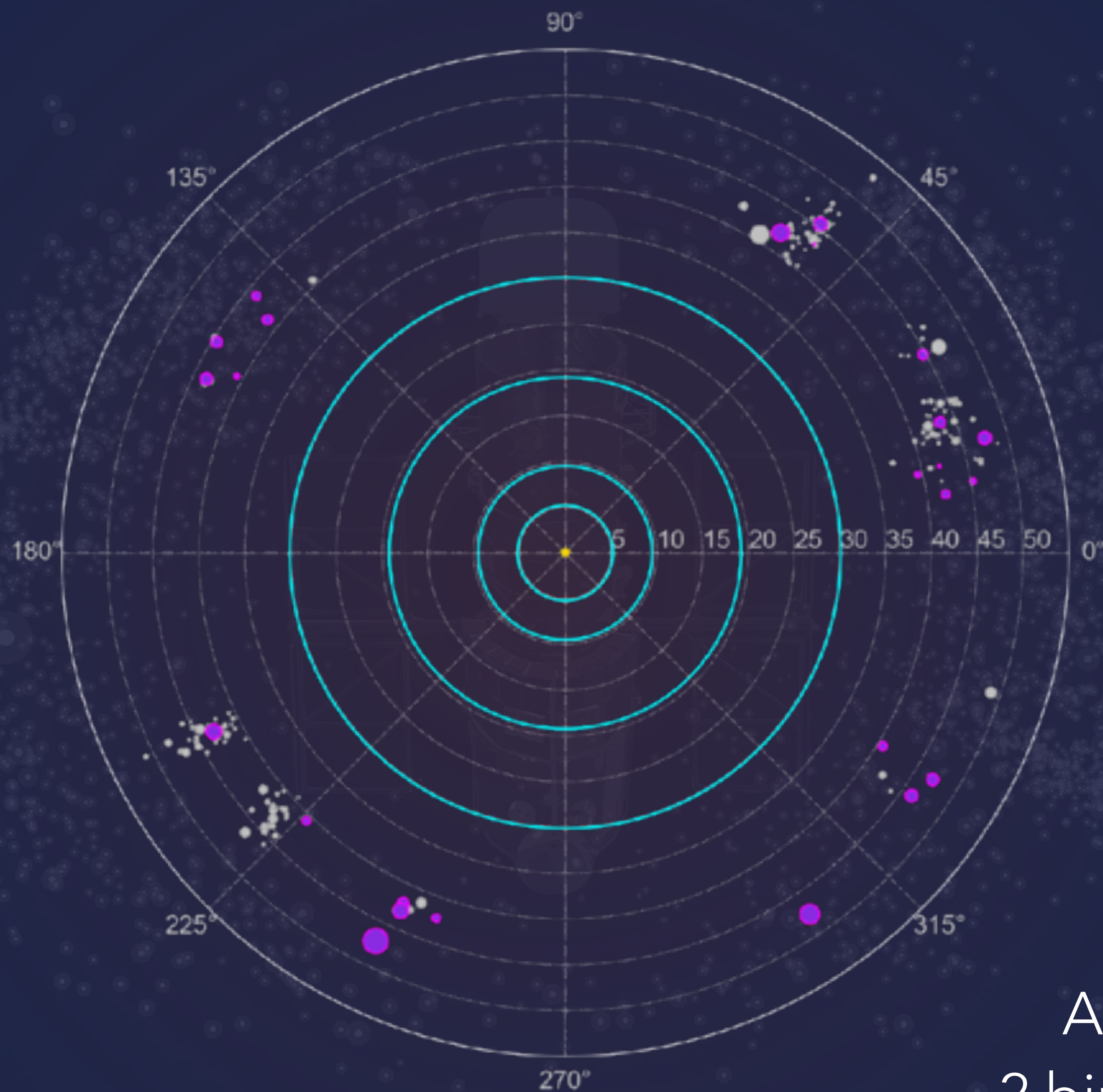


From: Parker 2021, "Transneptunian Space and the Post Pluto Paradigm" chapter in *Pluto System After New Horizons*, in press.

● Binaries (25)

● Solitary (172)

205 initial targets, 197
observations executed
successfully



Archival targets:
2 binaries, 13 solitary

ORIGIN OF BINARY SYSTEMS

THE SOLAR SYSTEM ORIGINS LEGACY SURVEY

Planetesimal Capture

Initial planetesimal population

Final planetesimal population

$H_0 - 0.75, 2M_0$
UNCORRELATED COLORS

$H_0 - 0.75, 2M_0$
UNCORRELATED COLORS



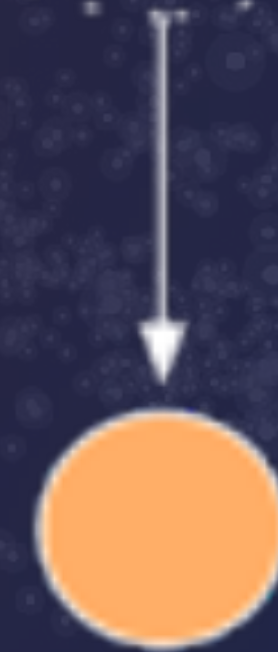
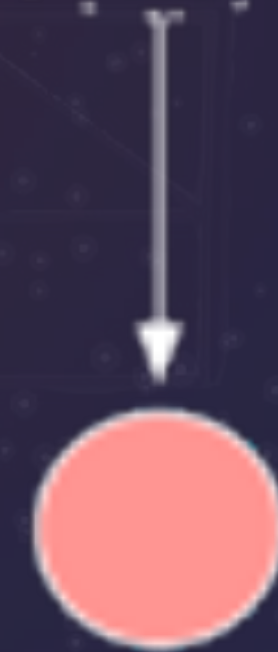
ORIGIN OF BINARY SYSTEMS

THE SOLAR SYSTEM ORIGINS LEGACY SURVEY

Pebble Collapse

Initial pebble
swarms

Final planetesimal
population



$H_0 - 0.25, M_0$
CORRELATED COLORS

$H_0 - 0.25, M_0$
CORRELATED COLORS

SSOLS

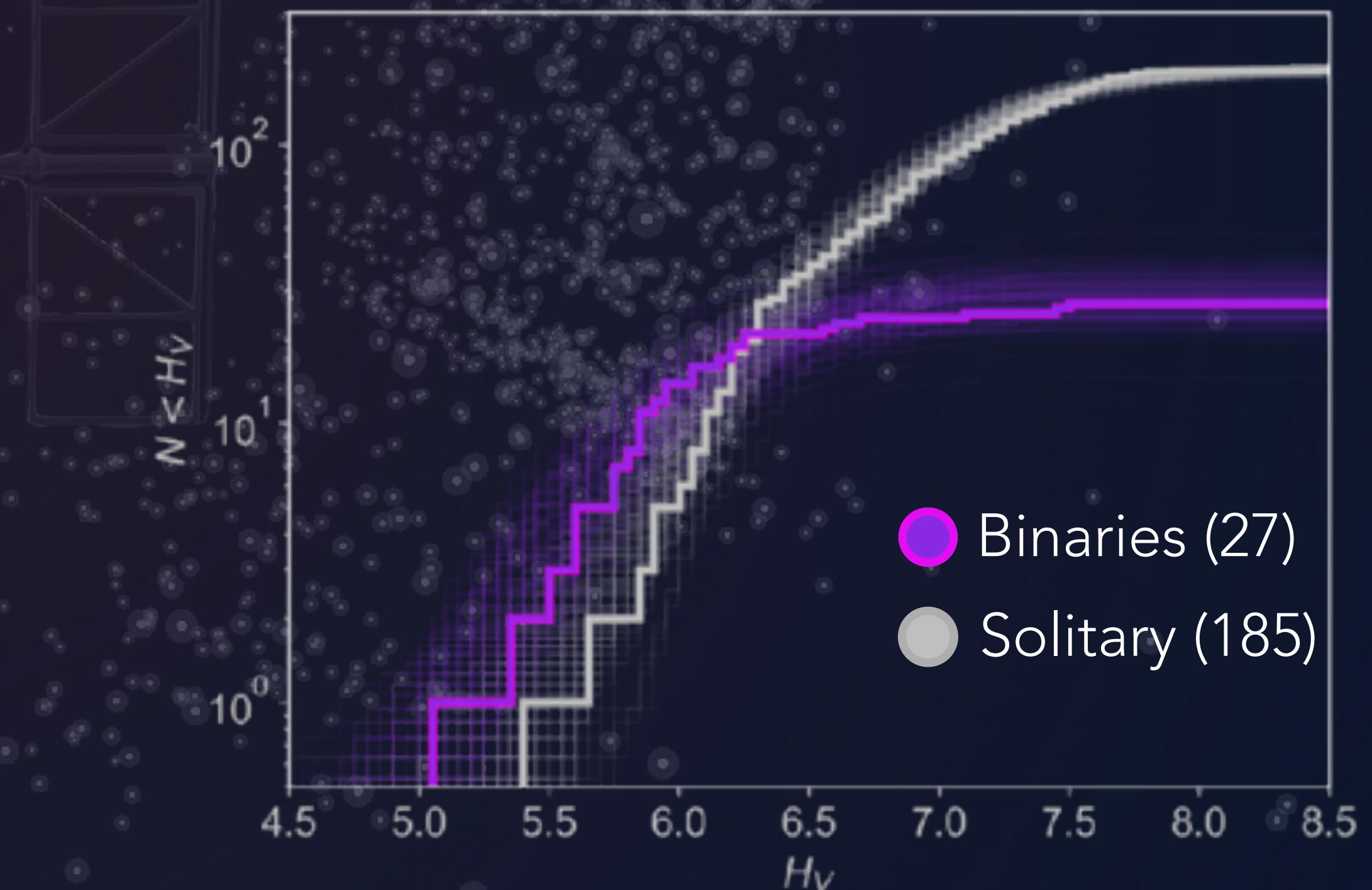
THE SOLAR SYSTEM ORIGINS LEGACY SURVEY

SSOLS is the first large, space-based, *calibrateable* survey of Cold Classical Kuiper Belt binary and V-I color properties.

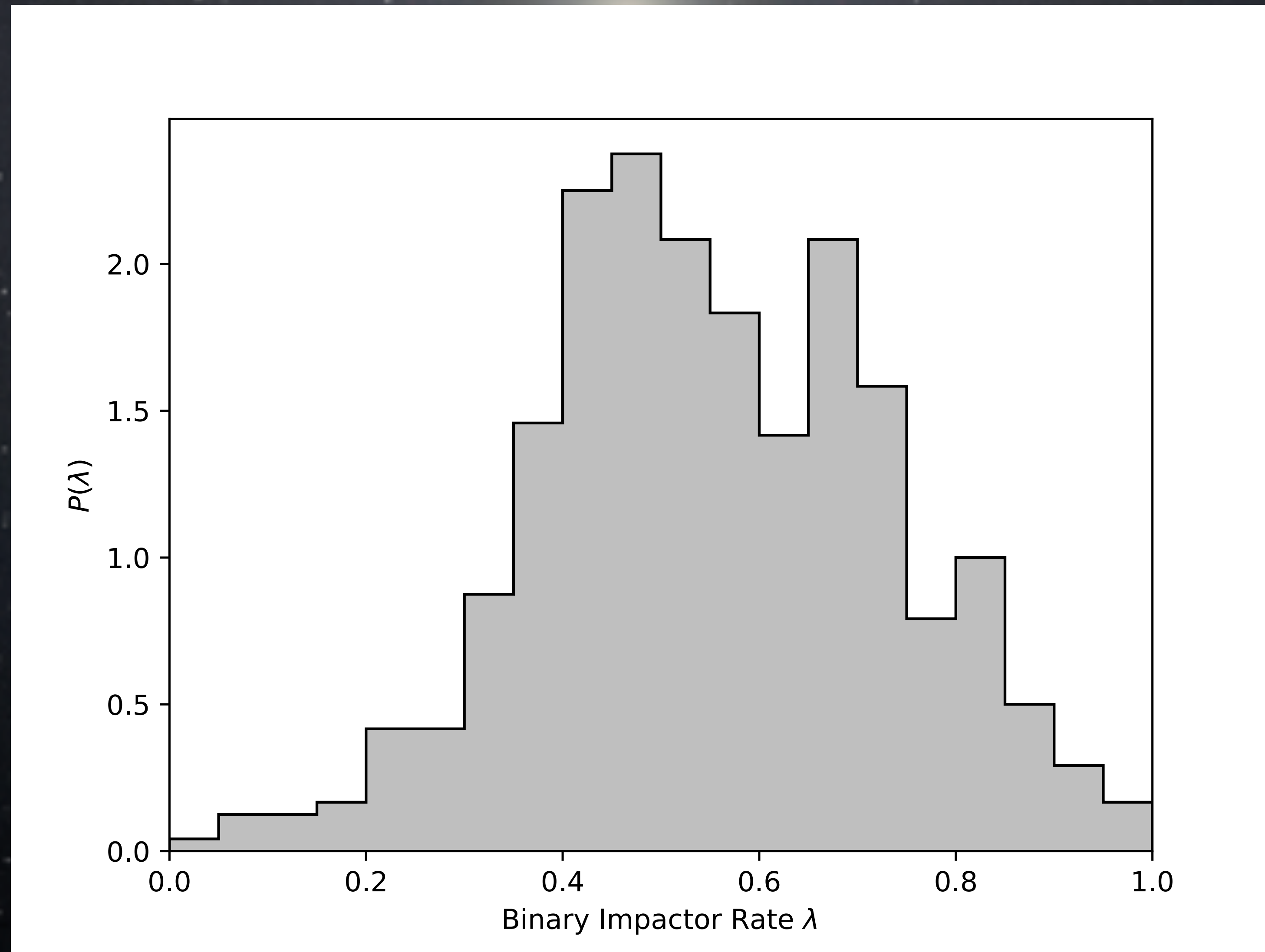
- A total successfully observed (197) + archival (15) sample of 212 cold classical Kuiper belt objects.
- All binary systems and most solitary objects have robust, resolved (V-I) colors from HST.
- All targets traceably discovered in the well-calibrated *CFEPS* or *OSSOS* programs.
- Only additional selection criteria for inclusion in sample: $H_r < 8$.
- Delivers a high-quality measurement of the luminosity function of binary systems and solitary objects *separately*.

Preliminary Findings:

- The *intrinsic* binary rate of cold classical Kuiper Belt Objects strongly depends on size for all orbital separations that can be observed with HST.
- **Binary rate: 13%-16% for $H < 6.2$, 1%-4% for $H > 6.2$**
- After accounting for all selection effects, the intrinsic binary rates are lower at *all* sizes than literature estimates of the apparent binary rate.
- Faint-object cold classical binary rate is comparable to other KBO populations at a few percent.



Pluto and Charon craters suggest tight binaries at small sizes.



From: Parker 2021, "Transneptunian Space and the Post Pluto Paradigm" chapter in *Pluto System After New Horizons*, in press.



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UPCOMING CAPABILITIES

Vera C. Rubin Observatory

See the LSST Science Book 2.0, chapter 5.

- Tens of thousands of TNOs/SDOs
- Very well-calibrated astrometry and photometry
- 5-band photometry
- Frequent revisits

Nancy Grace Roman Space Telescope

- 100x Hubble Space Telescope FoV; comparable sensitivity.
- High sensitivity, high resolution coronagraph: access to close-in faint satellites and ring structures.

JWST

See Parker et al. 2016 "Physical Characterization of TNOs with JWST" PASP 128

- Extraordinarily sensitive at fundamental bands of many key ice species
- Substantial GTO allocations for TNO science already

TAOS-II

- <https://taos2.asiaa.sinica.edu.tw>
- Dedicated three-telescope serendipitous stellar occultation facility
- Massive leap in high-cadence star-hours
- Directly measure SFD of small TNOs

WHAT IS MISSING?

Coordinated Theory/Modeling Efforts

- Planetary migration, collisional evolution, growth processes
- Internal evolution

Investment in Multi-Chord Occultation Capabilities

- Dense, fixed networks
- Nimble mobile networks

Dedicated Space-Based Facilities

- Hubble has been a crucial but difficult-to-obtain resource. Access to future shared facilities likely as hard or harder.

Consistent Inferential Frameworks

- Standards for model selection need attention
- Likelihood-free inference techniques provide a path forward for population synthesis

Strategy for Partitioning of Difficult-to-Reproduce Datasets

- Mission datasets are expensive, take a decade+ to repeat
- Same for huge survey datasets
- Once a population is completely surveyed, that's the sample we have.